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SOME ASPECTS OF THE EFFECT OF PLASTICITY ON THE AUXETIC BEHAVIOR

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Abstract The paper studies the effect of plasticity on the materials with negative Poisson's ratio. The macroscopic and the microscopic elasto-plastic behavior of a laminated aluminium composite plate reinforced with auxetic layers are investigated. The results show that auxetic effect persists and becomes stronger with increasing of the shear stress level. It was also shown that the effect of plasticity on auxeticity fades with the expansion of the plastic zone.

Key words: Auxetic material, negative Poisson's ratio, plasticity, micro-, and macro-scales modeling.

1. INTRODUCTION

Materials with negative Poisson's ratio are called auxetic materials [1]. The term *auxetic* is coming from the Greek word *auxetos*, meaning *that which may be increased*. Instead of getting thinner like an elongated elastic band when stretched, an auxetic material gains volume, expanding laterally. Auxetic materials of this type are expected to have interesting mechanical properties, such as high energy absorption, fracture toughness, indentation resistance and enhanced shear moduli, which may be useful in some applications, see e.g. [2-7]. Scientists have been aware of the existence of auxetic materials for over a hundred years, though without very special attention, and treating them as an accident or a curiosity. The auxetic materials include natural and man-made materials, covering from nano- to macro-scale and they span a large category of polymers, composites, metals and ceramics. In terms of natural materials, we have crystalline silicate, α-cristobalite, zeolites and a number of bio-materials such as skin, bone and early stage of embryonic tissue.

A series of composites have negative Poisson's ratio, especially laminated fiber reinforced composites and the phenomenon is observed by controlling buckling by tailoring laminates with in-plane restrained unloaded edges where Poisson's effect was predominant to the extent that caused premature instability and significant departure from classical behavior [8, 11]. Designs of composites with re-entrant honeycomb and hexagonal structures having negative Poisson's ratio (Fig. 1) were published in recent years [12-16].

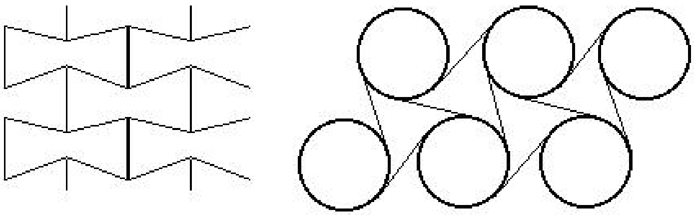

Fig. 1. Re-entrant honeycomb and hexagonal structures with negative Poisson's ratio.

The auxetic structure is generally anisotropic and the scale-dependent, that means the structure is deforming at a macroscopic or microstructural level, or even at the molecular levels [17-22].

In this paper, the auxetic hexachiral structures (Fig. 2) and auxetic hexagonal structures (Fig. 3) are analyzed from the point of the effect of plasticity on auxetic behavior. A chiral material is isotropic with respect to coordinate rotations but not with respect to inversions. Such a material will twist when stretched [23].

In [24], the studies have shown that auxetic effect persists and becomes even stronger with plastic yielding. This is a very important property for civil engineering applications that require higher shear modulus, indentation toughness and acoustic damping. It was also shown in [24] that the effect of plasticity on auxetic effect fades with the plastic zone expansion.

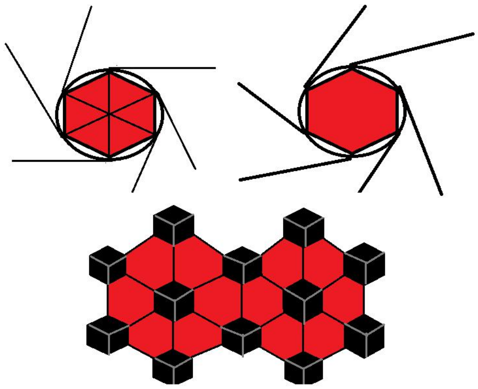

Fig. 2. Auxetic hexachiral structures.

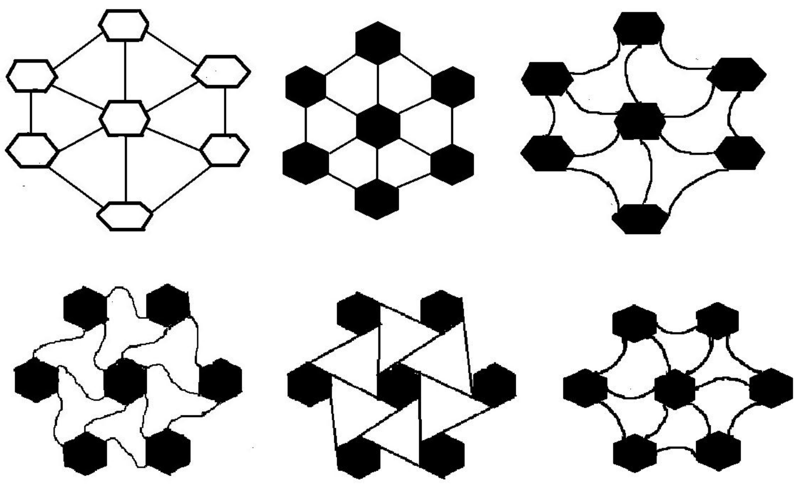

Fig. 3. Auxetic hexagonal structures.

2. THEORY

In this section, the macroscopic, the mesoscopic and the microscopic elasto-plastic behavior of a laminated aluminum composite plate reinforced with auxetic layers is considered, in the spirit of paper [8]. The paper [8] focuses on the application of the Cosserat theory [26] and Bécus homogenization technique [25] to derive the effective Young's modulus of the laminated composite plate based on auxetic materials.

Consider a laminated 2D composite plate which occupies the region $x \in [0, L]$, $z \in [-c, c]$, is made up of alternating N aluminium and auxetic material layers, normal to the direction x of wave propagation (Fig. 4). The layers are parallel, planar, periodical, across which the displacements are continuous. The length of each layer is l. The interfaces between the layers are located at nl, $n = 1, 2, ..., N$, and each joint has two faces identified by $+$ and $-$. Choose coordinates so that the waves lie in the (x, z) plane. The plate is assumed to be in plane strain and to support waves running along the x-direction.

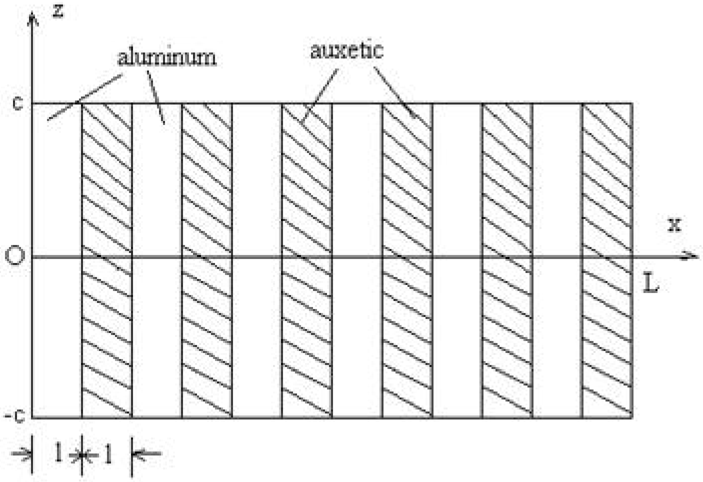

Fig. 4. Sketch of the composite plate.

The auxetic material has hexachiral structure shown in Fig. 2. Chirality is necessary for this structure to be auxetic.

We are interested in investigation the influence of the plasticity on the effective Young' modulus and Poisson's ratio ν of the laminated plate. The material constants C for this laminated composite are periodic functions of x

$$C(x + P) = C(x), \tag{1}$$

where P is the period equal to the length of the basic cell for the composite $P = 2l$, where $2l$ is the period represented by the length of the basic cell for the composite.

The material constants are $C = \{\lambda, \mu, \kappa, \alpha, \beta, \gamma, C_1, C_2, C_3\}$ where λ, and μ are Lamé elastic constants, κ is the Cosserat rotation modulus, α, β, γ, the Cosserat rotation gradient moduli, and C_i, $i = 1, 2, 3$ are the chiral elastic constants associated with non-centro-symmetry. For $C_i = 0$ the equations of isotropic micropolar elasticity are recovered. For $\alpha = \beta = \gamma = \kappa = 0$, the theory reduces to the classical isotropic linear elasticity [26].

At the mcro level, the yield function $f(\sigma)$ is given by

$$f(\sigma)=\sqrt{\frac{3}{2}\sigma^{dev}:\sigma^{dev}}-r_0-hp \quad , \tag{2}$$

where $\sigma^{eq}=\sqrt{\frac{3}{2}\sigma^{dev}:\sigma^{dev}}$ is the von Mises equivalent stress, σ^{dev} is the deviatoric part of the stress tensor, r_0 is the yield stress, h the hardening modulus and p is the cumulative plastic strain variable. The hardening modulus has values in the range $(100,1000)$ MPa.

At the macroscale, the yield function $f(\Sigma)$ is given by

$$f(\Sigma)=\sqrt{\frac{3}{2}c\Sigma^{dev}:\Sigma^{dev}+b(\mathrm{tr}\Sigma)^2} \ , \tag{3}$$

where Σ^{dev} is the deviatoric part of the stress tensor $\Sigma=\frac{1}{V}\int_V \sigma \mathrm{d}V$, with V the volume of the unit cell, $\mathrm{tr}\Sigma$ is the trace of the stress and c and b are coefficients related to the porosity related to the cell sizes. The conventional foam exhibits pores with average diameter around 900 μm. The manufacturing processes of compression used for obtaining the auxetic material from the conventional foam lead to a reduction of porosity (the cell sizes) [11]. The conventional foam has a Poisson's ratio positive of 0.25 at compressive strain of 10%, which decreases sharply with the increase of compressive loading, to become slightly negative from 60 to 80% of tensile strain. The auxetic foam exhibits a negative Poisson's ratio of -0.185 at compressive strain from 10 to 25%, showing a sharp increase for rising compressive strain, reaching then a zero value at 55% of compressive strain and a positive Poisson's ratio of 1.33 at 80% [22].

The homogenized elastic Young's modulus is given by [8]

$$E=F(C')+E' , \tag{4}$$

$$E'=\frac{(2\mu'+\kappa')(3\lambda'+2\mu'+\kappa_{aux})}{(2\lambda'+2\mu'+\kappa_{aux})}+\frac{1}{2}p^2 , \tag{5}$$

$$p^2=\frac{2\kappa_{aux}}{(K_0'^2-1)} , \tag{6}$$

$$K_0'^2=1+\frac{(C_{1aux}+C_{2aux}+C_{3aux})^2}{(\lambda'+2\mu'+\kappa_{aux})(\alpha_{aux}+\beta_{aux}+\gamma_{aux})} , \tag{7}$$

where C_{al} are the aluminum constants and C_{aux}, the auxetic constants. The function $F(C')$ is numerically determined only. Fig. 5 shows the variation of the Poisson's ratio with respect to the shear stress level. We see that the Poisson's ratio is decreasing as the shear stress level is increasing. Therefore, the auxetic effect persists and becomes stronger when the shear stress level is increasing.

The relationship between the Poisson's ratio and the size of the plastic zone into n unit cell is shown in Fig. 6. We see that the effect of plasticity on auxeticity fades with the expansion of the plastic zone.

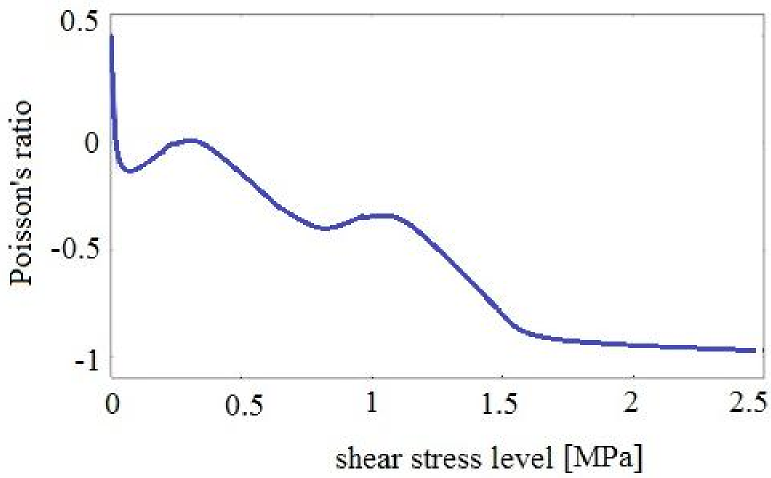

Fig. 5. The variation of the Poisson's ratio with respect to the shear stress level.

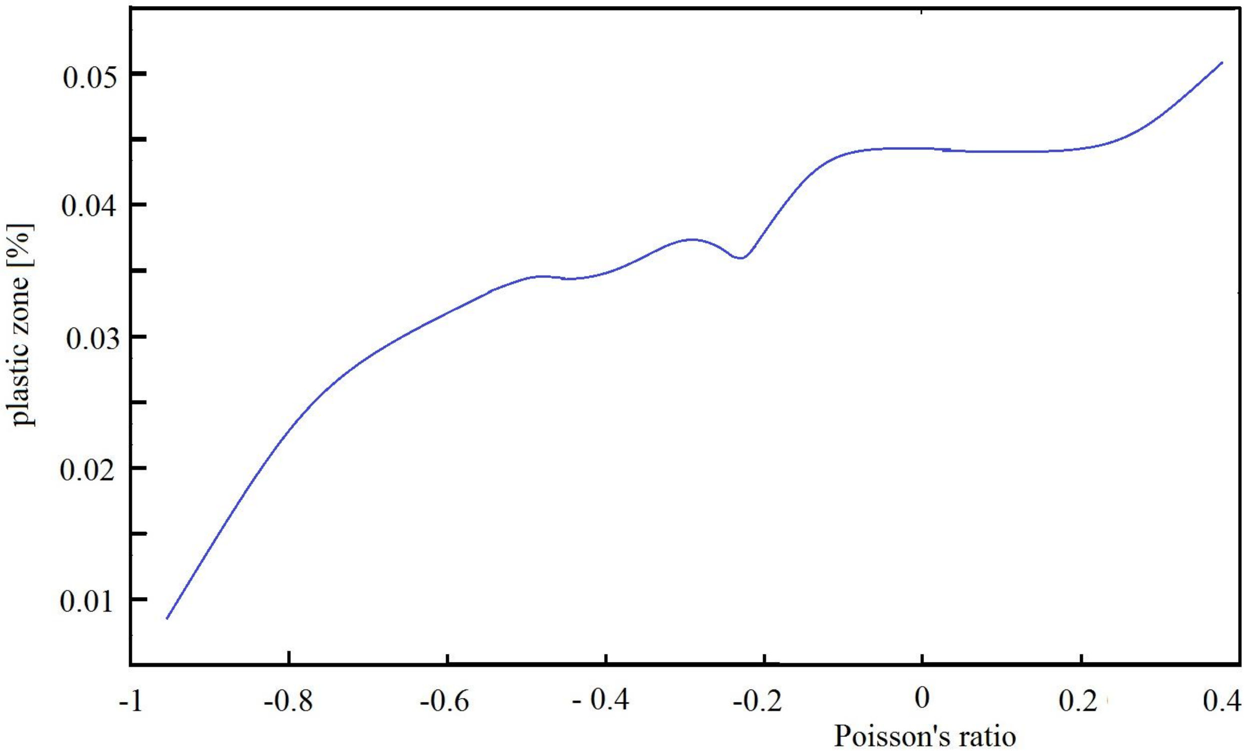

Fig. 6. The relationship between the Poisson's ratio and the expansion of the plastic zone into a unit cell.

The relationship between the load and the displacement for a material with positive Poisson's ratio 0.2 and 0.4, and the auxetic material with negative Poisson's ratio -0.4 and -0.2 are represented in Fig.7. For positive Poisson's ratio, the material exhibits the usual three stages behavior (elastic, plateau and densification), while the auxetic material exhibits single stage behavior, with a quasi-exponential dependence.

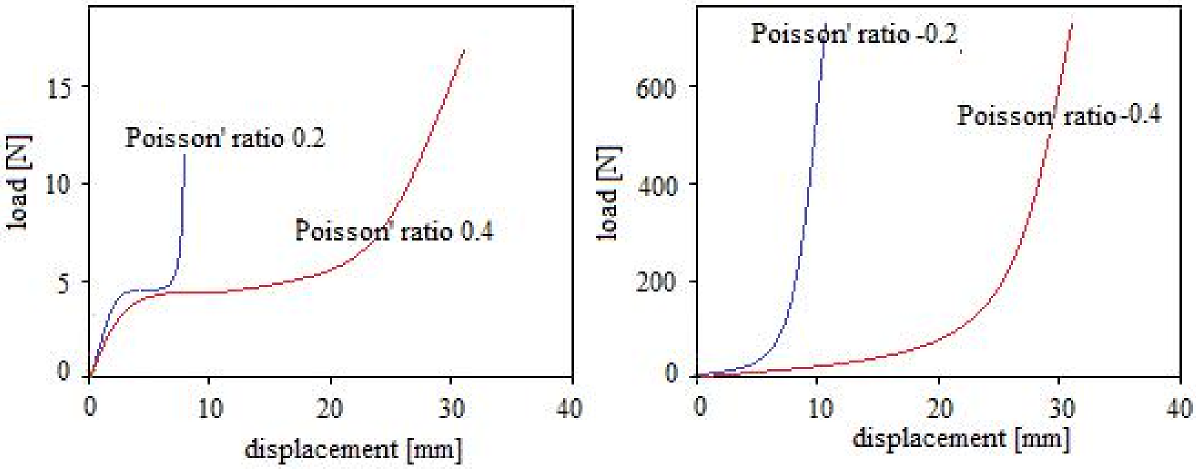

Fig. 7. The load-compressive displacement behavior of conventional material with positive Poisson's ratio and of the auxetic material, respectively.

3. CONCLUSIONS

In this paper, the effect of plasticity on the auxetic behavior of materials with negative Poisson's ratio. The macroscopic and the microscopic elasto-plastic behavior of a laminated aluminium composite plate reinforced with auxetic layers are investigated. The results show that auxetic effect persists and becomes stronger with increasing of the shear stress level. It was also shown that the effect of plasticity on auxeticity fades with the expansion of the plastic zone.

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